Final Technical Report

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TITLE OF AWARD:

A Gravity Study of Holocene-Active Structures in the Puget Lowland, Washington

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ABSTRACT:

We collected ~ 300 new closely spaced gravity measurements in the northern Puget Lowland in two areas thought to contain potentially active seismogenic structures: (1) between the southern margin of the Bellingham basin and the Drayton Harbor-Birch Bay magnetic lineament, and (2) between the eastern extension of the Tacoma fault and western extension of the White River fault, crossing the Muckleshoot basin. Field evidence from geodetic studies suggest that these faults play an important role in accommodating the ~ 8 mm/yr northward movement of tectonic blocks within the convergent margin formed by the Juan de Fuca and North America plates. In addition, several geologic studies suggest that these faults have been active in Holocene time and pose a significant earthquake hazard. The new data were merged with the existing potential field database for use in developing new models for both the Bellingham and Muckleshoot basins. Results of the study suggest that (1) the Bellingham basin is segmented into at least two, possibly three, sub-basins that are divided by the southeastern extension of the Birch Bay fault; (2) the northern boundary of the Bellingham basin may be farther south than previously thought, and (3) the Muckleshoot basin appears to be bisected along a trend extending from the White River fault to the southeast of the basin and continuing to the eastern end of the Seattle fault to the northwest.

REPORT:

Introduction. The Pacific Northwest, situated at near the intersection of the North America plate and the obliquely subducting Juan de Fuca plate, is commonly recognized as a region of high earthquake hazard. Evidence from the geologic record indicates a large subduction zone event occurred in A.D. 1700 (estimated M > 8) and several large, shallower events occurred about 1100 years ago (e.g., Atwater and Moore, 1992; Nelson et al., 2003; Sherrod et al., 2004). Based largely on findings from paleoseismic studies, the average recurrence for Benioff-zone ruptures in northern Cascadia is now estimated at about 500 years. The historical record indicates that 11 earthquakes of M ≥5 have occurred in the Seattle vicinity in the past century (http://www.PNSN.org). These crustal faults must play an important role in accommodating strain imparted by the Juan de Fuca plate as it subducts beneath the western U.S. margin. Similarly, deep structural basins sandwiched between these fault systems evolved as a result of plate interactions and continue to deform today in response to several millimeters of northward-directed motion and clockwise rotation of the forearc (Figure 1; McCaffrey et al., 2007; 2013). An obstacle to our understanding of these subsurface structures and their role in strain build-up and release is that many are covered by Quaternary sediments or obscured by urbanization. To model crustal deformation and the seismogenic potential of faults or fault segments, a better understanding of fault system dimensions, potential interactions among faults, and structural ties between fault systems and adjacent basins is needed. Towards this end, we acquired ~ 300 new gravity measurements in two areas of the Puget Lowlands (Figure 1). The measurements were designed to address gaps in existing data coverage and to construct new potential field models for areas in which Holocene-active crustal faults are thought to exist. The study was aimed at revealing how the fault systems might interconnect beneath the deep forearc basins that sit adjacent to heavily populated urban centers. The study addresses two significant research topics: (1) the possible relation of the White River fault to the well-studied Tacoma and Seattle faults and adjacent Muckleshoot and Tacoma basins, and (2) the potential relation of the recently discovered uplift terraces in the Birch Bay-Drayton Harbor to locally pronounced aeromagnetic and topographic lineaments seen in recently acquired LiDAR data. The acquired gravity data and developed potential field models (1) refine interpretations of subsurface structures that have been identified in previous geologic studies, (2) complement high-resolution aeromagnetic data and seismic reflection data by offering an independent constraint on anomalies and structures, (3) improve estimates of fault dimensions, and (4) assist in the interpretation of fault relationships suggested by recent geologic and paleoseismic studies.

Data Acquisition: Fieldwork to acquire the new gravity data took place in June 2011 and July 2011. The first field site focused on the Bellingham basin and the Drayton Harbor-Birch Bay magnetic lineaments (Figures 2 and 3). Existing gravity data in this area were sparse and station spacing was unevenly distributed. During the field campaign for the Bellingham study site, measurements at approximately 150 new locations were acquired (Figure 2). The locations were chosen so as to provide uniformly distributed station spacing (~ 1 measurement per square kilometer) for later gridding. In addition, gravity data were collected near Birch Bay, along transects roughly perpendicular to the strike of the Drayton Harbor lineament to allow for the construction of 2D models of potentially active structures identified in LiDAR data and associated with subsidence and uplift in coastal areas (Figures 3 and 4; Kelsey et al., 2012). All gravity data were collected using a Lacoste-Romberg Model G gravimeter. All data locations and station elevations were determined using a Trimble GeoXT GPS unit.

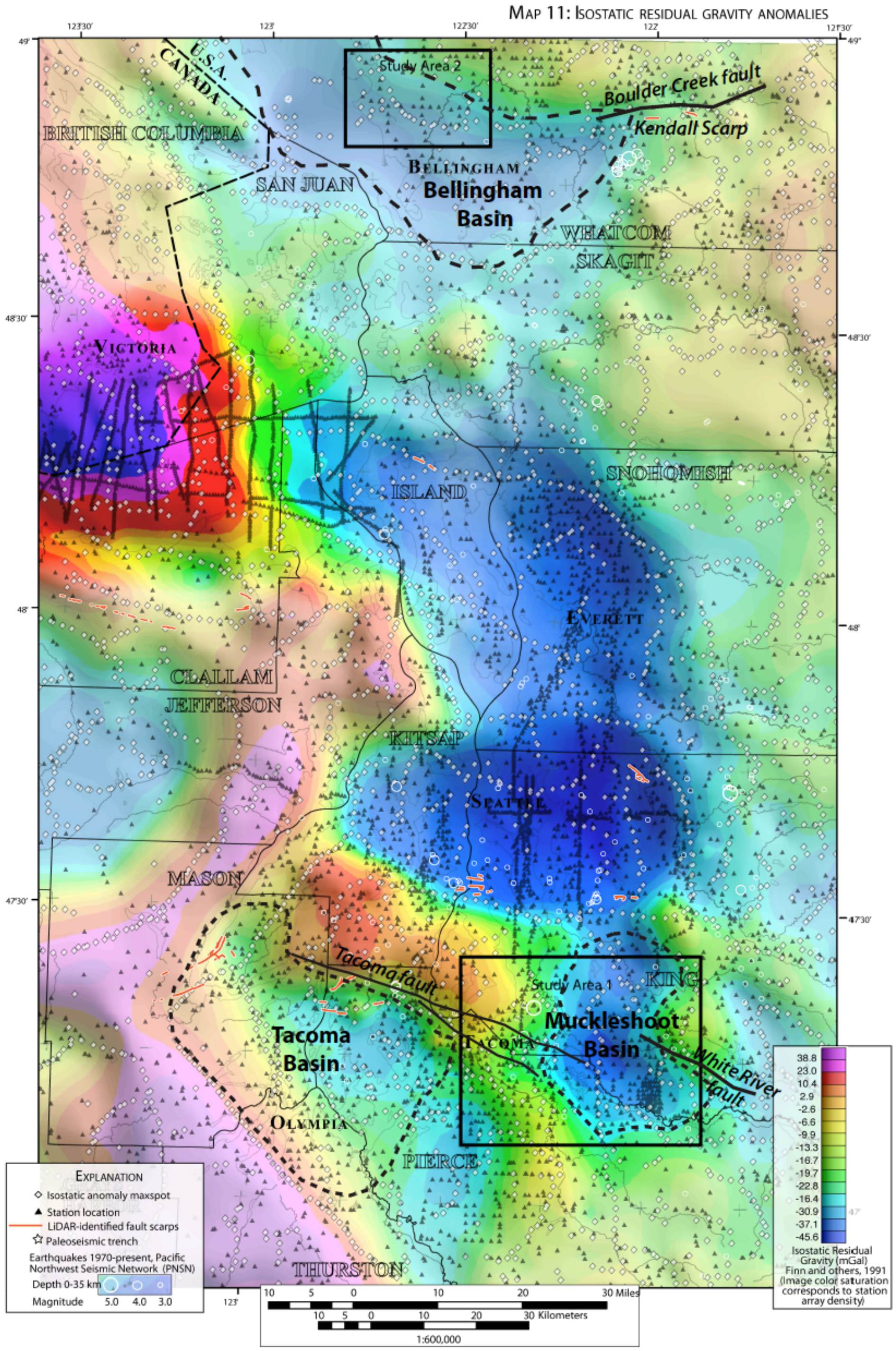

Figure 1. Isostatic residual gravity (Finn et al., 1991; Blakely, pers. comm.), showing locations of the two project study areas. Pronounced gravity lows define basins, which are sandwiched between major faults. Study areas shown with black boxes. North site focuses on recently discovered deformation at north side of the Bellingham Basin Birch Bay and an active subsurface fault on the north side of the Bellingham Basin. Southern site focuses on the possible kinematic relation of the White River fault to the Tacoma fault and the currently deforming Muckleshoot Basin.

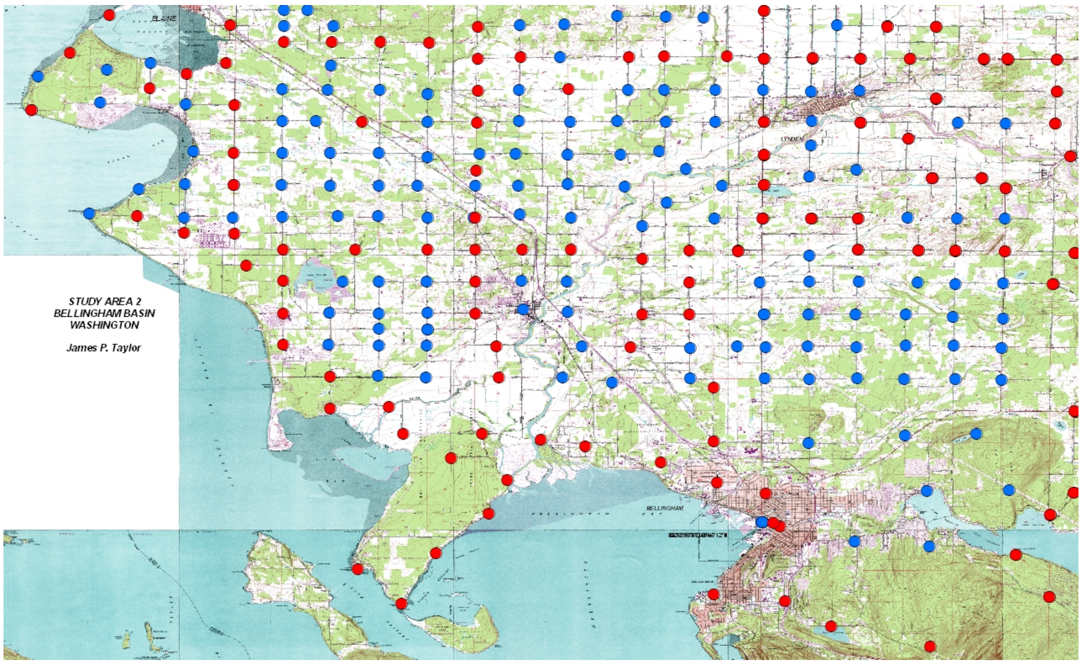

Figure 2. Location of June 2011 field site north of Bellingham, WA. Pre-existing sites=Red dots. Newly acquired sites in this study=Blue dots.

Locations and elevations were differentially corrected in post-processing to achieve an estimated accuracy of sub-meter scale. Once the data acquisition in the Bellingham area was complete, the team travelled to the second field site to set up a local base station in the town of Covington. This was achieved by looping between the Covington site and an established base station in Tacoma. About 150 new gravity measurements were collected in the second field area, specifically focusing on the Muckleshoot basin (Figure 5).

Data Processing: The new gravity measurements taken for this study were corrected for instrument drift using a standard looping procedure and established base stations. Drift was assumed to be linear over the time of the loop. Subsequent data processing included the free-air, Bouguer, latitude, tide and terrain corrections (Blakely, 1995). Gravity values from prior surveys were already reduced and new data were merged with these existing data. Several stations from previous surveys were re-occupied in this study to check agreement between data sets. Average error for gravity values was ±1.37 mGal.

Total magnetic field data used in the study were provided by the U.S. Geological Survey (R. Blakely, pers. Communication, 2011) and later reduced to pole for modeling. Profiles of both gravity and magnetic data were chosen for cross-section modeling using OASIS Montaj™ and its 2.5 D modeling extension, GM-SYS™.

Several field separation techniques were used to highlight shallow structures that might be associated with faults. Figures 6 and 7 show the results of applying a vertical derivative filter to both the complete Bouguer gravity (CBA) and Total Magnetic Field anomaly (TFA) data, respectively, from the Bellingham site. Figures 8 and 9 show the same technique applied to the potential field data from the Muckleshoot basin site.

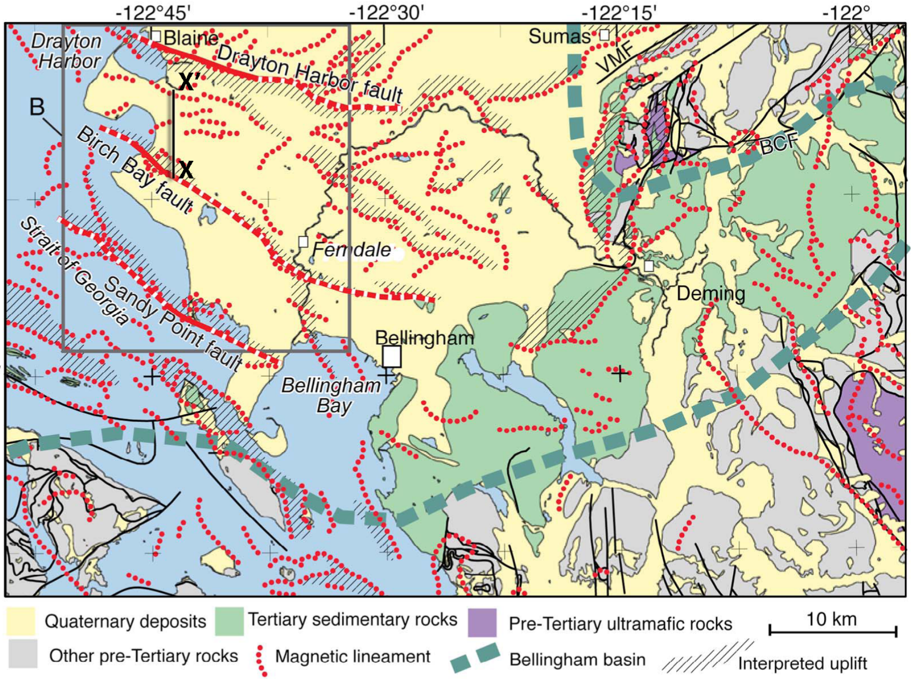

Figure 3. Simplified geologic map of Bellingham basin showing locations of Holocene-active faults. Right panel: LiDAR DEM with Holocene-active fautls superimposed (from Kelsey et al., 2012).

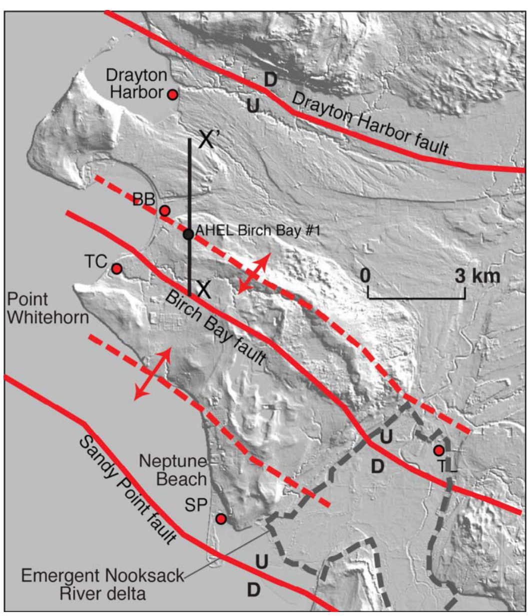

Figure 4. LiDAR DEM with Holocene-active faults superimposed (from Kelsey et al., 2012).

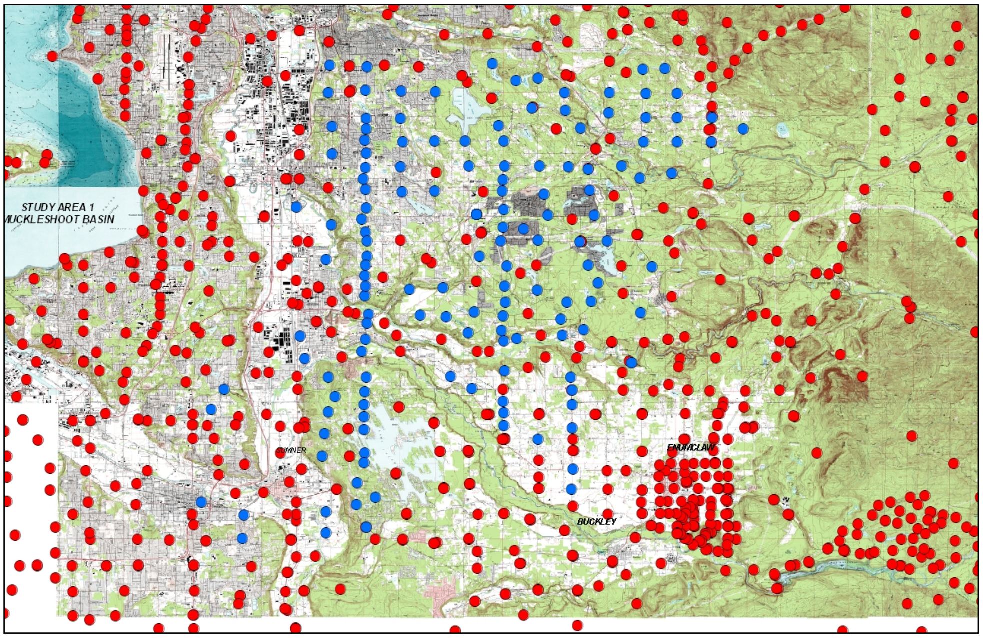

Figure 5. Location of July 2011 field site near Covington, WA. Pre-existing sites=Red dots. Newly acquired sites in this study=Blue dots.

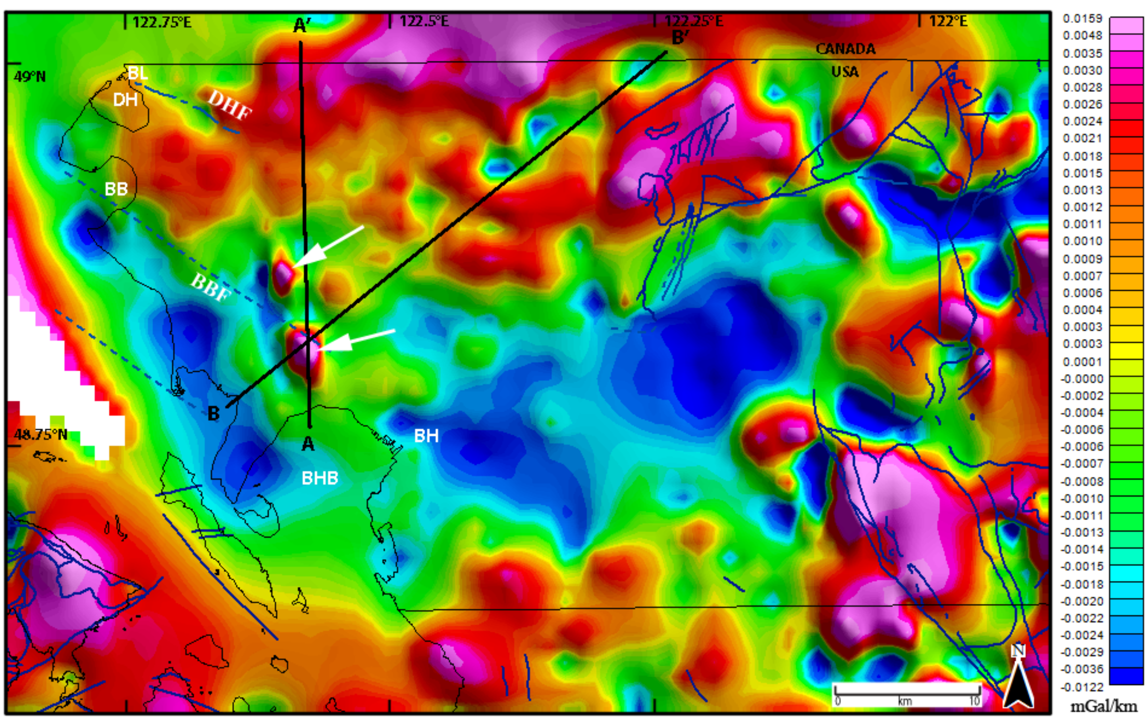

Figure 6. Gravity (CBA) map of the Bellingham study area with vertical derivative filter applied. A-A′ and B-B′=profile locations. Solid blue lines=faults. Dashed blue lines=inferred faults. White arrows=previously unseen high gravity anomalies. Abbreviations: BB=Birch Bay, BH=Bellingham, BHB=Bellingham Bay, BL=Blaine, DH=Drayton Harbor, DHF=Drayton Harbor fault, BBF=Birch Bay fault.

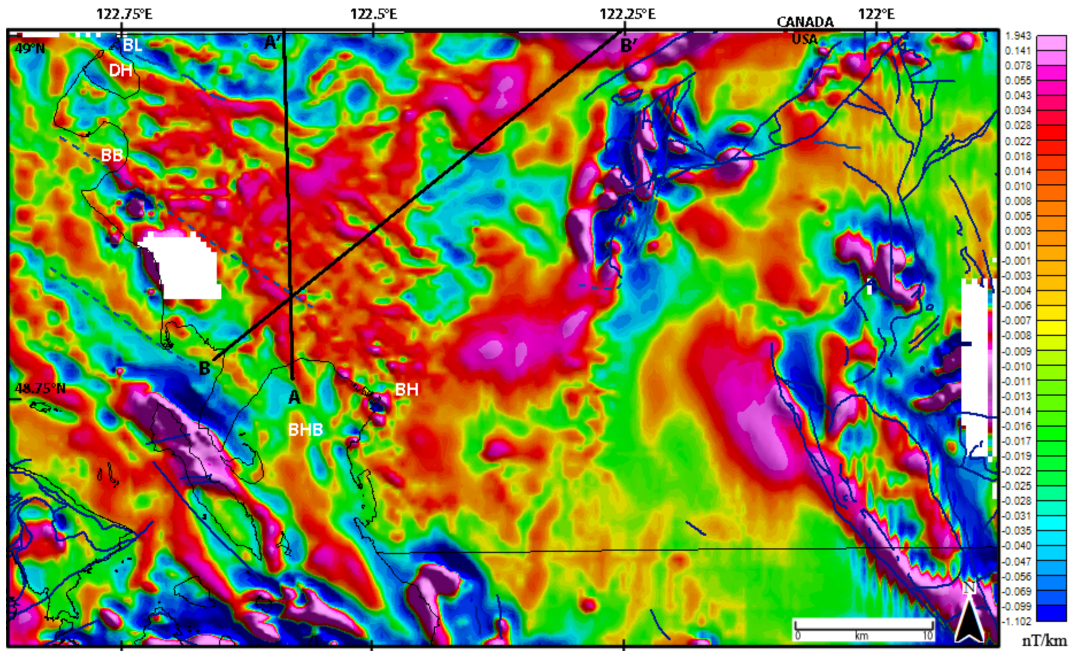

Figure 7. Magnetic (TFA) map of the Bellingham study area with vertical derivative filter applied. A-A′ and B-B′=profile locations. Solid blue lines=faults. Dashed blue lines=inferred faults. Abbreviations: BB=Birch Bay, BH=Bellingham, BHB=Bellingham Bay, BL=Blaine, DH=Drayton Harbor.

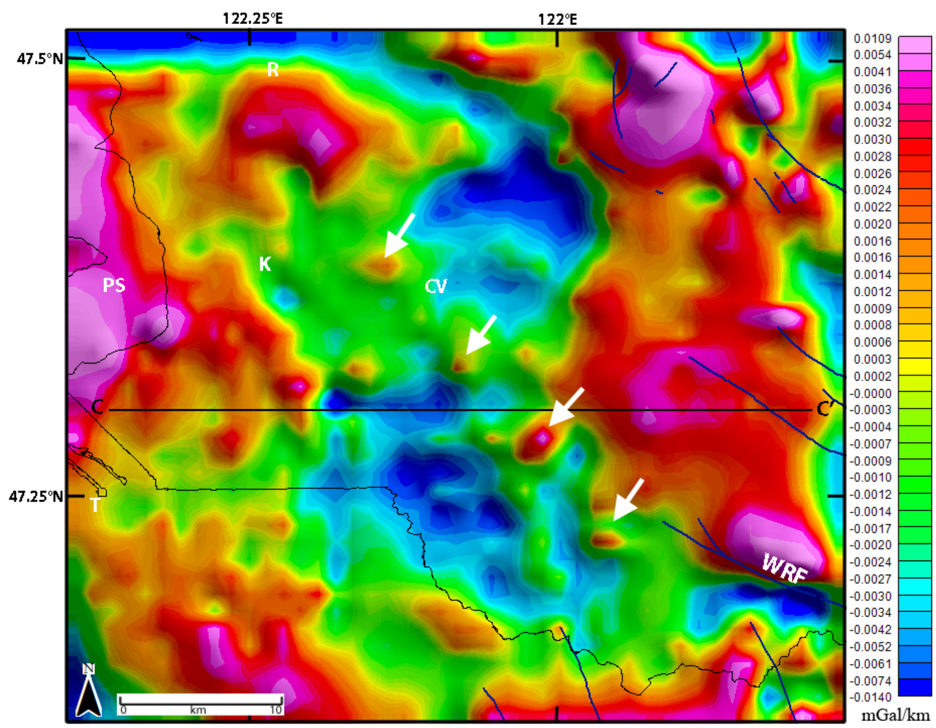

Figure 8. Gravity (CBA) map of the Muckleshoot study area with vertical derivative filter applied. C-C′=profile location. Solid blue lines=faults. Arrows=aligned gravity highs. Abbreviations: CV=Covington, K=Kent, PS=Puget Sound, R=Renton, T=Tacoma, WRF=White River fault.

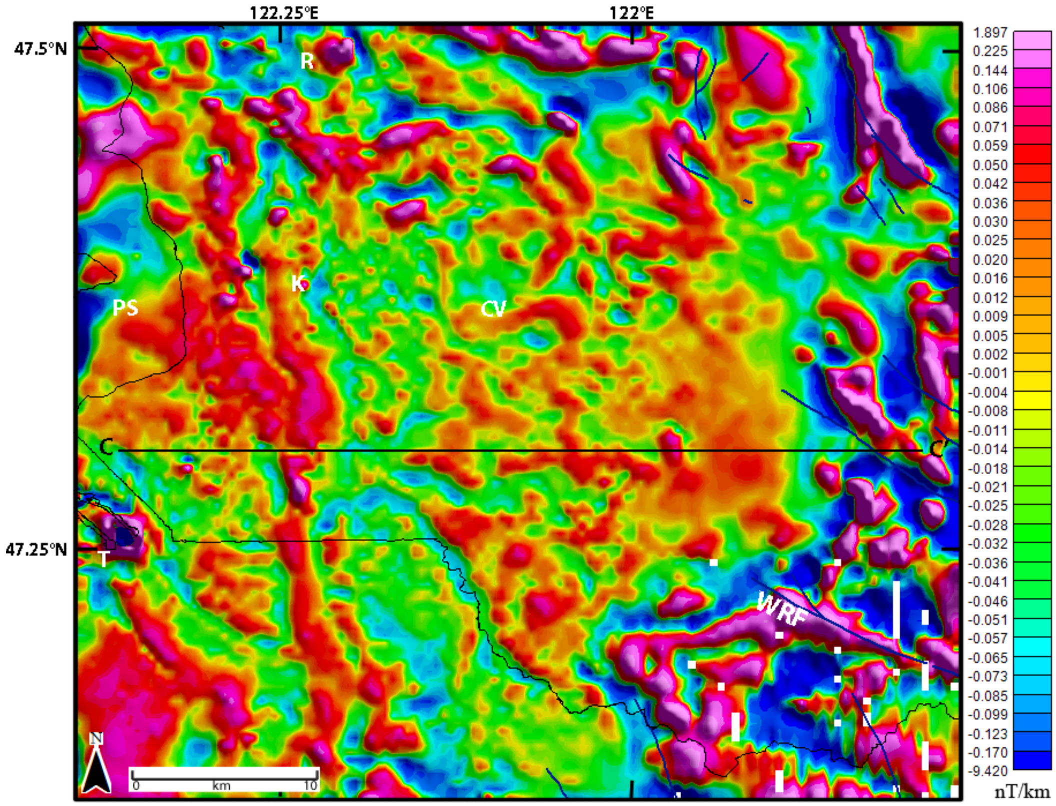

Figure 9. Magnetic (TFA) map of the Muckleshoot study area with vertical derivative filter applied. C-C′=profile location. Solid blue lines=faults. Abbreviations: CV=Covington, K=Kent, PS=Puget Sound, R=Renton, T=Tacoma, WRF=White River fault.

Investigation Results: Previously published models of the Bellingham basin suggest that its northern boundary follows the Border Creek fault (BCF in Figure 3) westward toward the town of Sumas, then diverting northward into Canada. The filtered gravity data shown in Figure 6, however, suggest that the northern boundary of the Bellingham basin continues westward at Sumas, following a gentle arc and eventually merging with the Birch Bay fault. In addition, results of the modeling suggest that the basin may be segmented into several smaller sub-basins that are locally separated by gravity highs (Figure 6). A pronounced magnetic gradient follows the Birch Bay fault (BBF) and can be traced into the basin for over 20 km from the coast (Figure 7). This result, combined with cross-sectional models along profiles A-A' and B-B' (Figures 10 and 11), suggests that the BBF is a major structural feature. To the north, the Drayton Harbor fault (DHF) appears as a magnetic lineament that bisects two areas of relatively high gravity values. From its expression near the coast, it extends to the southeast and appears to follow the basin boundary, parallel to the BBF. Results from cross-sectional modeling, however, suggests that the Drayton Harbor fault is not associated with major offsets at depth; rather, it may represent a youthful structure that is currently developing in response to ongoing plate motions.

Filtered gravity data from the Muckleshoot basin (Figure 8) show a gravity low that is bisected by a northwest trending gravity high (indicated by white arrows). Two gravity lows, one near Tacoma (T) and the other near Renton (R) in Figure 8, suggest that these features may be associated with the Tacoma and Seattle faults, respectively. To the southeast, the White River fault juxtaposes a gravity high with a gravity low, and follows a northwesterly trajectory through the basin. Although the gravity data suggest that the White River fault continues to the northwest, it is not clear whether it bends eastward to connect to the Tacoma fault, or alternatively, continues to the northwest to link with the east-trending Seattle fault system. Magnetic data (Figure 9), filtered to highlight shallow crustal features, do not lend insight into this question. Additional modeling may help to clarify these relationships.

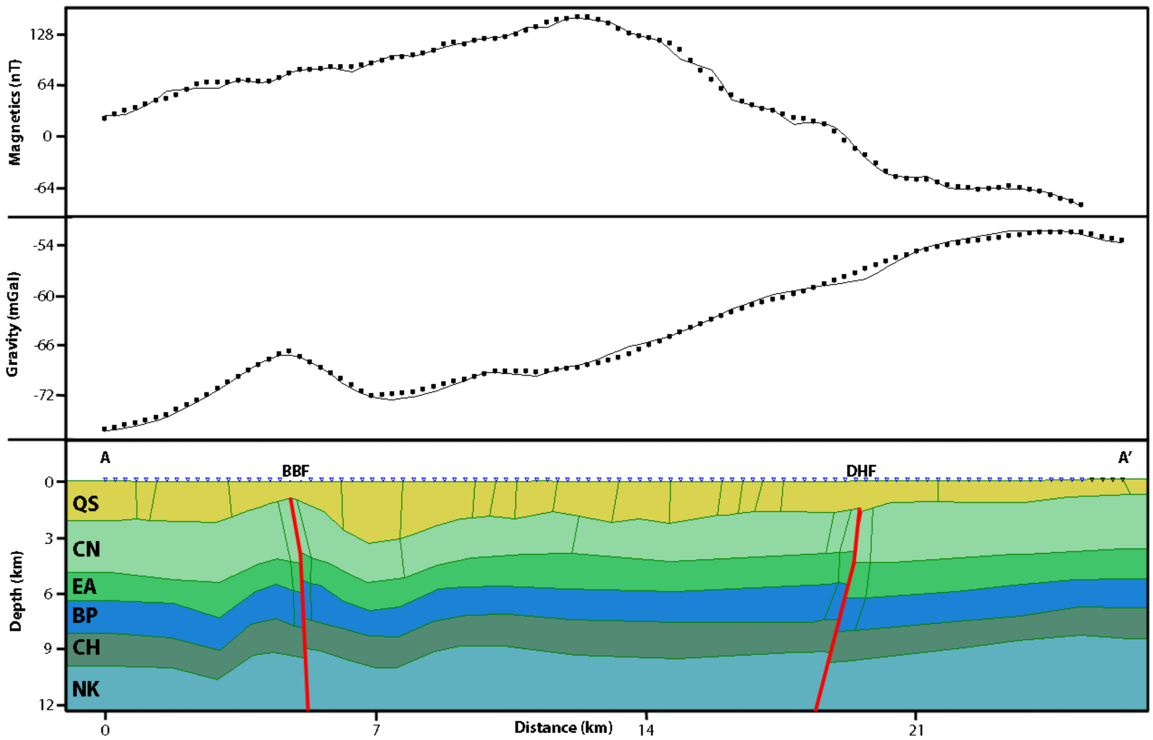

Figure 10. N-S gravity and magnetic profile with geologic cross-section for A-A′ (see Fig. 6 for location). Abbreviations: QS= Quaternary Sediments, CN= Chuckanut Formation, EA= Easton Metamorphic Suite, BP= Bell Pass Mélange, CH= Chiliwack Group, NK= Nooksack Formation, BBF=Birch Bay Fault, DHF=Drayton Harbor Fault.

Publications and/or presentations to date: Formal presentations of the acquired data and results were made at the Fall 2013 AGU annual meeting (Taylor et al., 2013; http://abstractsearch.agu.org/meetings/2013/FM/sections/GP/sessions/GP51C/abstracts/GP51C-1096.html). The work resulted in one M.S. thesis for James P. Taylor from Auburn University (Taylor, 2013; http://etd.auburn.edu/handle/10415/3614). A professional article is currently being preparded for pulication with co-authors (Blakely (USGS), Sherrod (USGS), Taylor (Unit Corp) and Brown (U Washington).

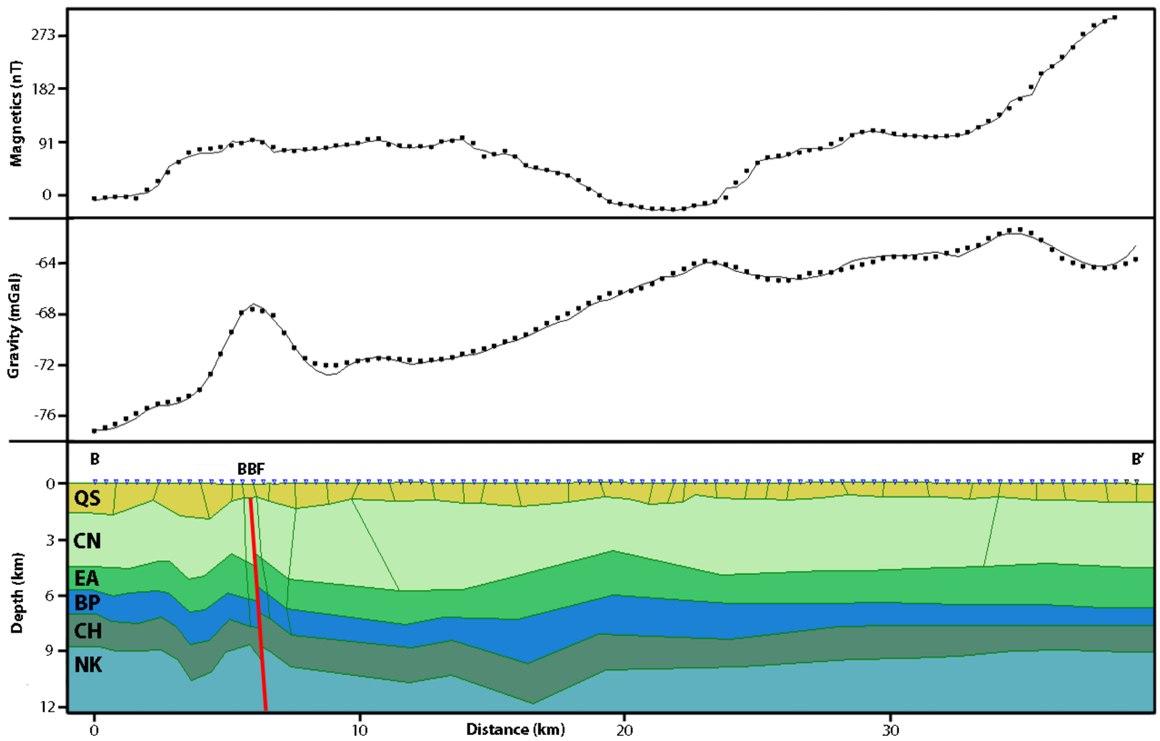

Figure 11. Gravity and magnetic profiles with geologic cross-section for B-B′ (see Fig. 6 for location). Abbreviations: QS= Quaternary Sediments, CN= Chuckanut Formation, EA= Easton Metamorphic Suite, BP= Bell Pass Mélange, CH= Chiliwack Group, NK= Nooksack Formation, BBF=Birch Bay Fault.

References Cited:

Atwater, B. F., and Moore, A. L. (1992). A tsunami about 1000 years ago in Puget Sound, Washington, *Science 258*: *5088*, 1614-1617.

Blakely, R. J. (1995). *Potential Theory in Gravity and Magnetic Applications*, Cambridge University Press, New York., 441 p.

Finn, C., Phillips, W. M., and Williams, D. L. (1991). Gravity anomaly and terrain maps of Washington, scale 1:500,000 and 1:1,000,000, *U.S. Geological Survey Geophysical Investigations Map, GP-988*.

Kelsey, H. M., Sherrod, B. L., Blakely, R. J., and Haugerud, R. A. (2012). Holocene faulting in the Bellingham forearc basin: Upper plate deformation at the northern end of the Cascadia subduction zone, *Journal of Geophysical Research 117*, *B03409*, doi:10.1029/2011JB008816.

McCaffrey, R., Qamar, A.I., King, R.W., Wells, R., Khazaradze, G., Williams, C.A., Stevens, C.W., Vollick, J.J. & Zwick, P.C. (2007). Fault locking, block rotation and crustal deformation in the Pacific Northwest, *Geophysical Journal International 169, 3*, 1315-1340.

McCaffrey, R., King, R. W., Payne, S. J., Lancaster, M. (2013). Active tectonics of northwestern U.S. inferred from GPS-derived surface velocities, *Journal of Geophysical Research 118.B2*, 709-723.

Nelson, C. H., Goldfinger, C., Johnson, J. E., & Gutierrez-Pastor, J. (2003). Holocene history of great earthquakes in the cascadia subduction zone based on the turbidite event stratigraphy. *EOS, Transactions, American Geophysical Union 84,46*, 1.

Sherrod, B.L., Brocher, T.M., Weaver, C.S., Bucknam, R.C., Blakely, R.J., Kelsey, H.M., Nelson, A.R. & Haugerud, R. (2004). Holocene fault scarps near Tacoma, Washington, USA, *Geology 32: 1*, 9-12.

Taylor, J. P. (2013). A Gravity Study of Holocene Active Structures in the Puget Sound Lowland of Washington State (M. S. Thesis). Auburn University, Auburn, AL.

Taylor, J. P., Wolf, L. W., Blakely, R. J., Sherrod, B. L., and Brown, J. M. (2013). Deformation of the Bellingham Basin in the Northern Cascadia forearc as inferred from potential field data, Abstract GP51C-1096 AGU Fall Meeting, San Francisco, Calif.